Reduce Booster Beam Loss Using New Corrector Magnets

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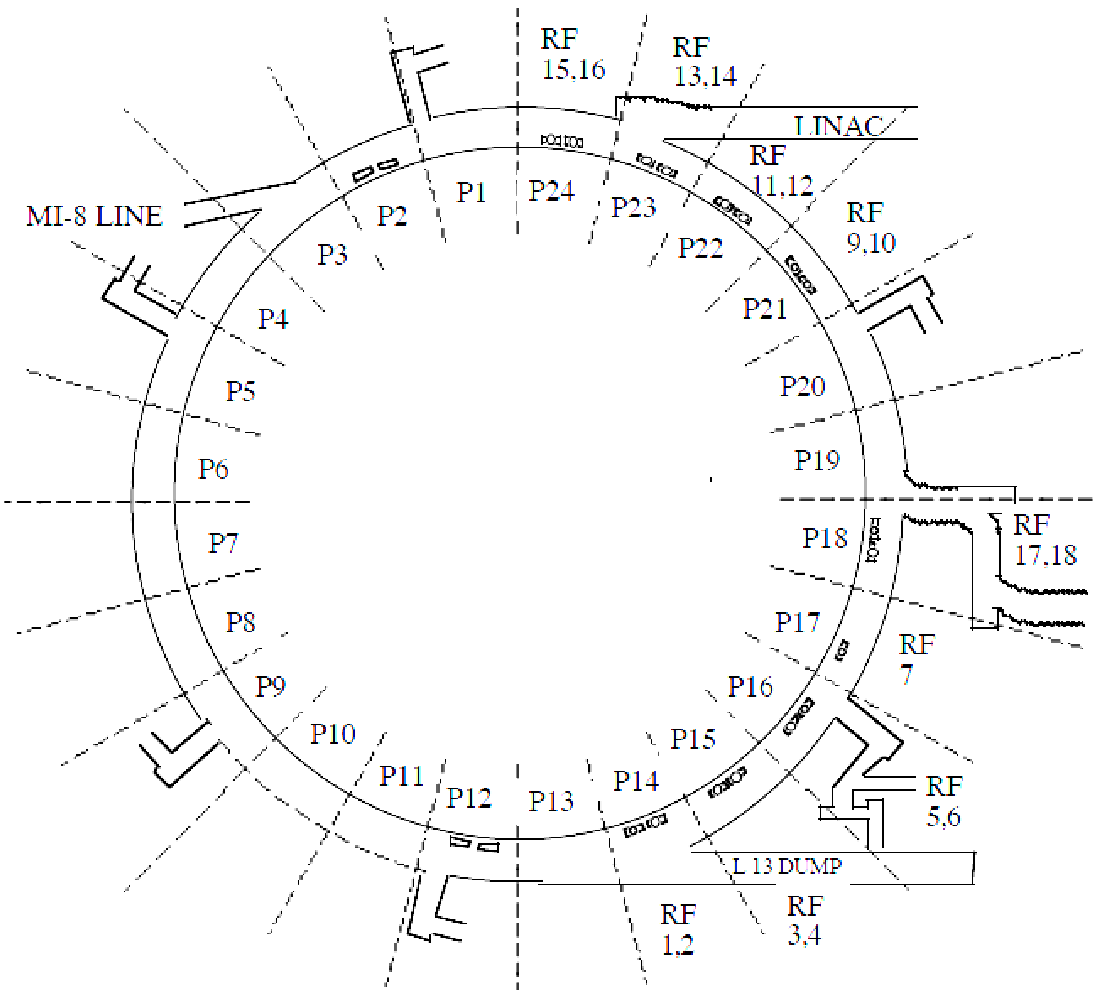
Fermilab Booster



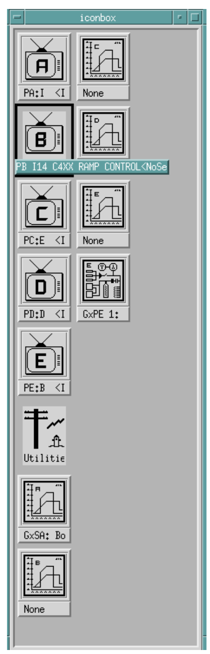
One Booster period: FOFDOOD, 2 F magnets, and 2 DF, with 6 meter long straight section and 1.2 meter short straight section. 24 long and 24 short straight sections. Standard cell length is 19.76m.

Introduction

The motivation behind this research lies in the demand in the intensity frontier of Fermilab. For example, LBNE (Long Base-line Neutrino Experiment), a proposed experiment after the Tevatron experiment shuts down, will require a much higher intensity of protons for neutrino production. Fermilab Booster as the most upstream circular accelerator, and the only accelerator to go through transition, calls in need for ½ reduction of beam loss in next year or so. Current method of changing beta function to reduce beam loss involves only single quad bump, which is found to have caused beta distortion everywhere else in the cycle, and has not achieved ideal correction to beam size. But to put several quad bumps together in a calculated ratio can localize such beta change and preserve beta function elsewhere. Other concerns about quad bump are that they should preserve the tune and the steering error should be corrected. Our solutions to the first is to use tune conserving multiple quad bump (4 quad bump and 5 quad bump, instead of 3 quad bump), and dipole compensation correspondingly. We found experimentally that we are able to compensate the steering error with dipoles on both planes. We did aperture scan at long 6 near the collimator, and see whether we are able to achieve changing the beam size (beta function) at the desired location (injection).

1 Acnet

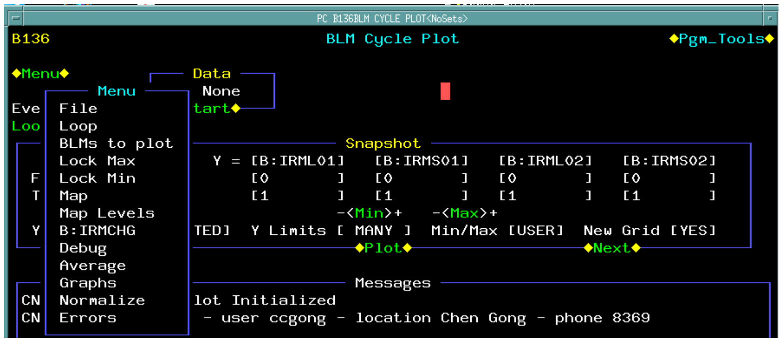
The main menu provides functional windows (e.g. PA), three plotting windows (e.g. GxSA) and a Utilities window for plots.



Acnet can be runned from other networks using VPN (go through same port). Otherwise it can only run within Fermilab network, at least with full access to all the pages. To do any real change to settings, it has to be accessed from console stations at the Main Control Room.

Console station: every stations beam switch has to be on in order for beam to run at a particular cycle. Switch off to reduce radiation and save energy when one does not need beam.

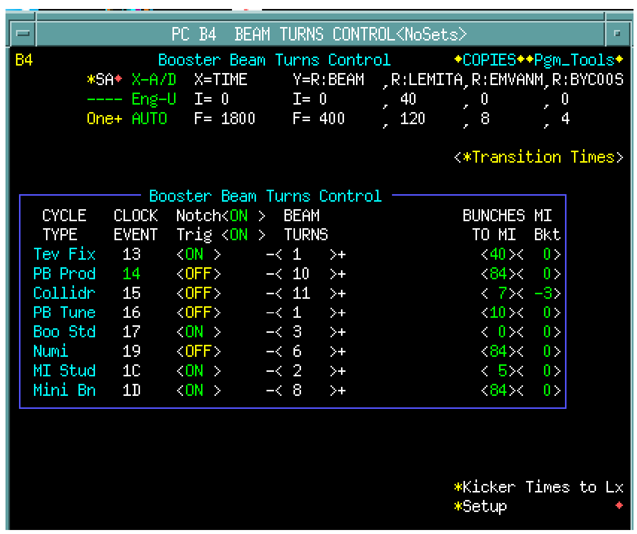
1.1 B136: beam loss:



- BLMs to plot: can select CHg0, normal magnets and special magnets.
- No loop (stop after taking data)
- Average: 3 and above for good data
- Data taken from Meghan's experiment during the first week (10A bump on short quads, start from 2.9ms to 7.3 ms): See **Appendix A** charts "s1" to "s24" (missing short12)
- Plot of beam loss throughout cycle for each setting, but abandoned due to the bad BLM washed the changes away: See **Appendix A** "beam loss diff at the location of mag"

1.2 B4: cycle control

- Acnet page B4



Booster study cycle 17 beam turns: usually1 to 2 turns, sometimes 3 turns (esp. towards shut down, the intensity was lowered). 17 is lower than other cycle because: we don't want to waste energy and cause radiation if don't have to, low intensity suffices study purposes.

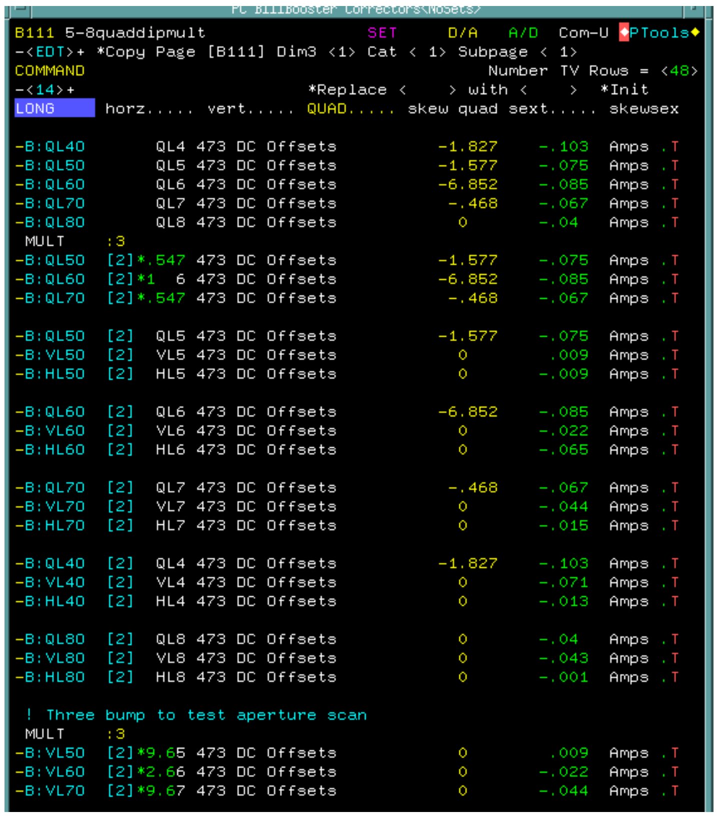
- Booster clock event: on local console in MCR, a handy tool to monitor Booster events.

1.3 B111: Booster Corrector parameter page (the new B11)

- Page location: B111 LONG QUAD page 14 to 17
- "[2]" stands for table entry 3 of the settings, in order to avoid messing up other cycles, we point only 17 cycle to table entry 3, and all other cycles stay at entry 1.

- “B:QL5” stands for read out of the quad value (ramp and DC), “B:QL5O” means only the DC offset value. Numbers in yellow shows the setting, those in green is readout at any instance (doesn’t give information of the setting)
- To set up a “MULT” on the page, type “MULT: x”, where x = number of devices in the mult. Point cursor to the blank location right above the yellow numbers and press “++” or turn the knob, all the devices in the mult will now ramp up and down together in proportional to the ration given in the mult setting.
- To copy a subpage at any location to another subpage location (this is how I moved the mult subpages from initially B11 to the new parameter page B111), go to a blank page where you want to have some page to be copied to, choose FTP on a subpage, click “FTP” and under it “page edit” and type in location of the page to be copied. Dimension “Dim3” in B111 is the choice between LONG and SHORT, “Cat” is the choice between ‘horz’, ‘vert’, ‘quad’, etc., “subpage” being the subpage number under such dimension and Category.

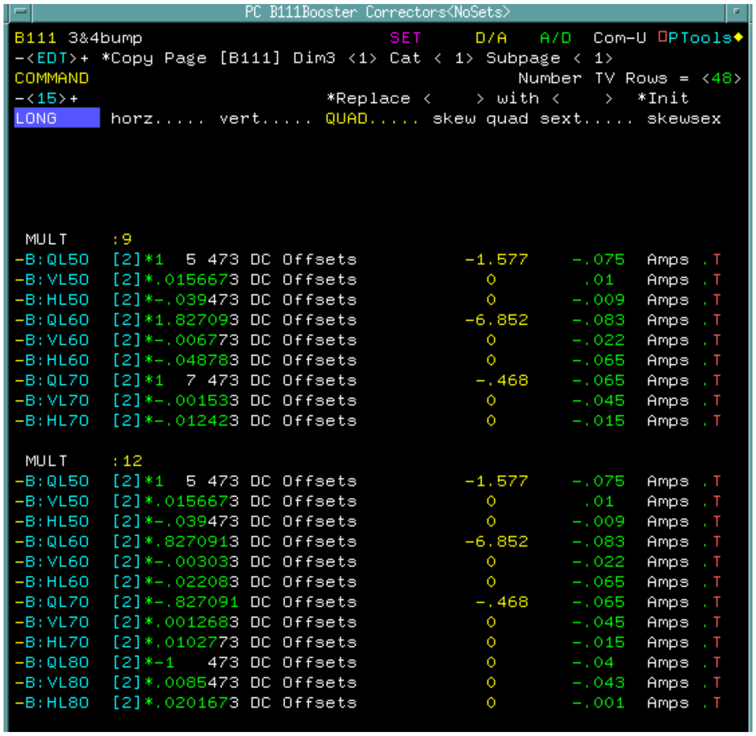
- Page 14:



From top:

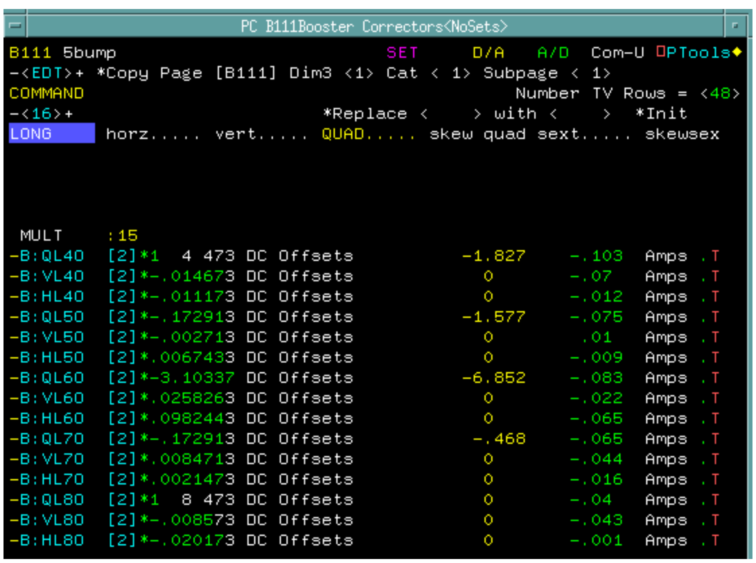
- Five individual quadruples at the location where we insert quadruple bump;
- A 3-bump without dipole compensation, the 3-bump is in ratio .547:1:.547, QL6 puts a constraint on the size of the mult;
- In order to find dipole compensations (both H and V) we listed magnets in the five periods;
- Dipole 3-bump for aperture scan.

- Page 15:



- Quad three bump with dipole compensation (dipoles ratio are found experimentally) (QL6 put a constraint on the size of this mult)
- Quad four bump with dipole compensation (dipoles ratio are found experimentally) (QL5 put a constraint on the size of this mult)

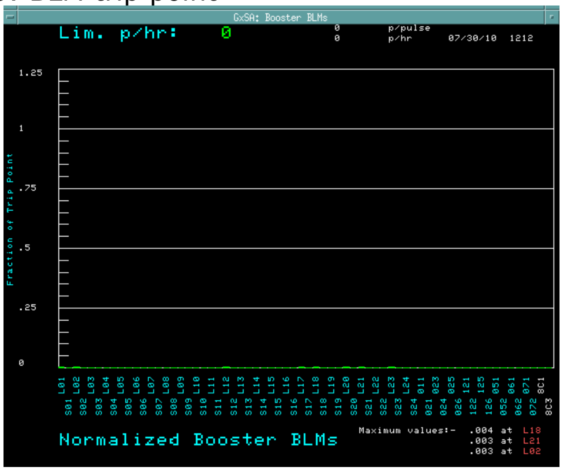
- Page 16



- Quad five bump with dipole compensation (dipoles ratio were first found experimentally, and later refined when five bump was activated) (QL6 put a constraint on the size of this mult).

- Page 17: 5bump without any dipole compensation.

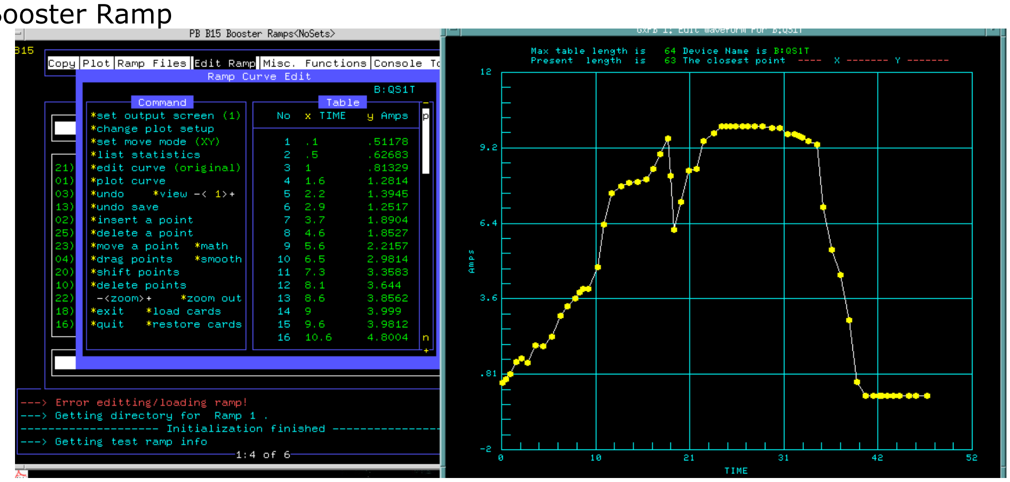
1.4 B88: BLM trip point



(snapshot taken during shutdown)

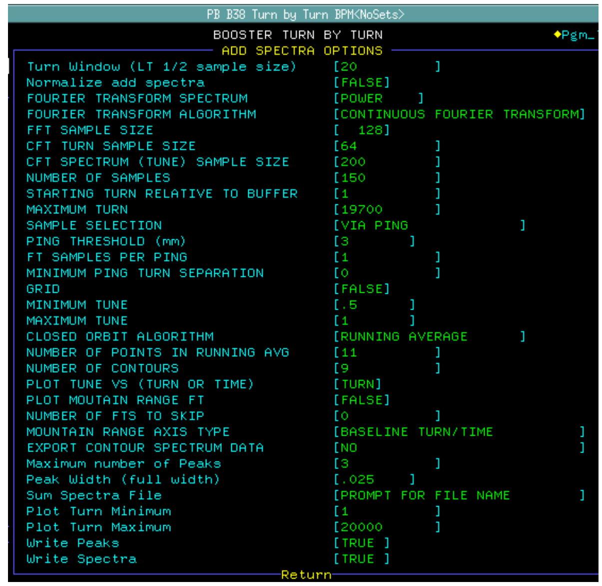
- It is normalized (so loss is shown as percentage of its trip point, any of the BLMs hit 1, Booster shuts off) over 100s running average.
- A good way to see if there is anything that is seriously wrong with what we do with the 17 cycle.

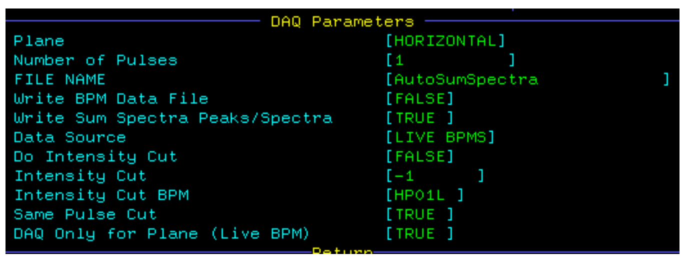
1.5 B15: Booster Ramp



- Put bump on quad ramps.
- Choose Edit Ramp: select a device ramp
  1) The current curve of the ramp is found experimentally;
  2) Can drag points up and down;
  3) Can go to "math" and input how much bump you want to put in and at which interval.

1.6 B38: tune measurement





Measure the tune using the B38 application (notes by Meghan McAteer, see **Appendix D** for full instructions)

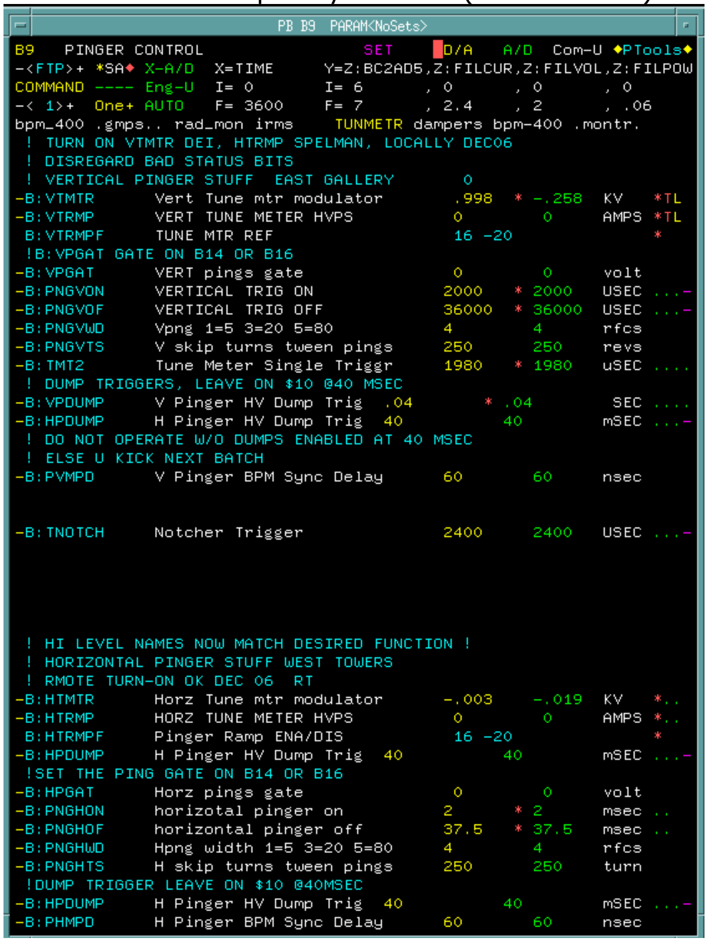
1. Every time you open B38, change the following options:
   a. go to Read Multiple BPM Options and change the number of turns from 20,000 to 10,000, in two places on the options screen (this just saves time by only reading in the first half of the acceleration cycle)
   b. go to Sum FT Spectra Options; change "CFT Spectrum (Tune) Sample Size" to 10,000 (this is the number of points in the Fourier transform); change "Closed Orbit Algorithm" to "Linear Fit"; change "Write Spectra" to "False"
   c. Enter "17" in the Digitize on Event slot
2. Select Auto DAQ Sum FT Spectra to begin a tune measurement, and change the following options:
   a. change "Plane" to "Vertical"; change "Number of Pulses" to 5 (this is how many separate Booster pulses will be measured and averaged); change "Do Intensity Cut" to "True", and change "Intensity Cut" to "-0.2" (this will make the program notice if there's not actually any beam in the machine when it's trying to measure the tune, and discard that bad data set)
   b. under "File Name", type in the name that you want for the data file. Call the files "5yS01" through "5yS24", and "5yL01" through "5yL24" (5 is the approximate time in the cycle that we're measuring, y is for vertical plane, S or L is for short or long section)
   c. Click Return, and the process should start. If you get any messages saying "*** is on when it should be off", just click ok. It will take about fifteen minutes or so for all of the data to be read in. When you get a message

saying that the auto sum daq has been successfully completed; it's done; you can move on to another magnet

d. This program seems to slow down when it's been running for a while. If you notice that it's taking longer than usual, closing and restarting B38 should help. Just remember to reset all of the options when you re-open the program.

1.7 B9: Pinger

Pinger is a small magnet that will give the beam a flicker and is able to do a Fourier Transform from time domain to frequency domain (tune domain).

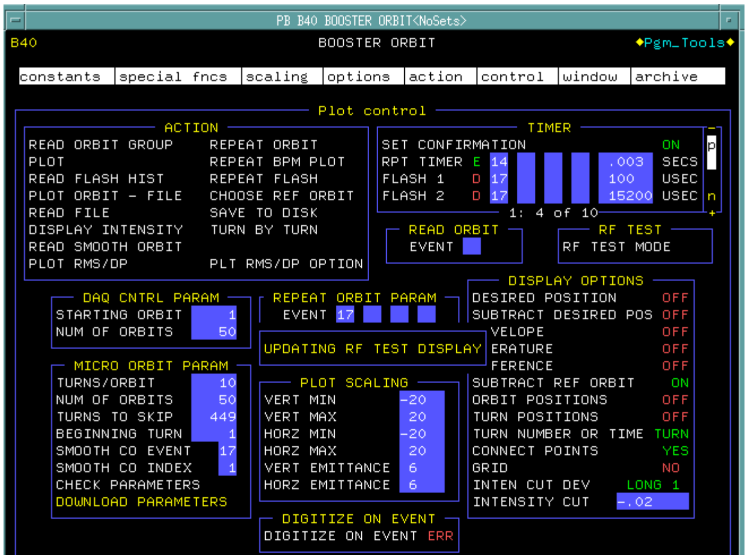


To turn on the pinger (before do turn-by-turn tune measurement):
Turn on 3 things: B:HTMTR, B:HTRMP, B:HTRMPF;
Set B:PNGHON to cycle 17 when using pinger, set to "FE" when turning pinger off.

1.8 B40: Booster orbit

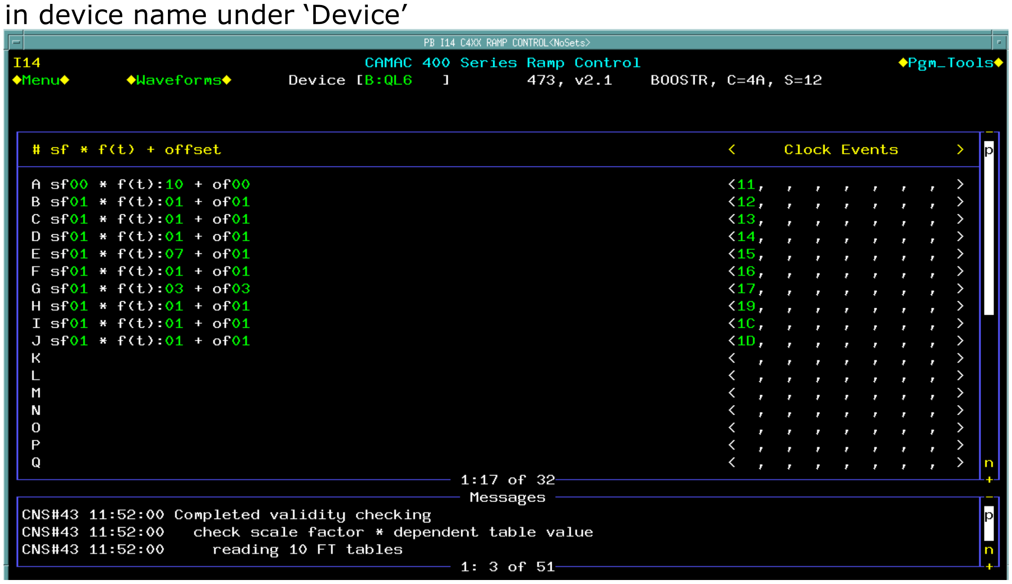
Change all cycles to 17. 'Turns to skip' set to 449. 'Digitize to event' should be set to 17.

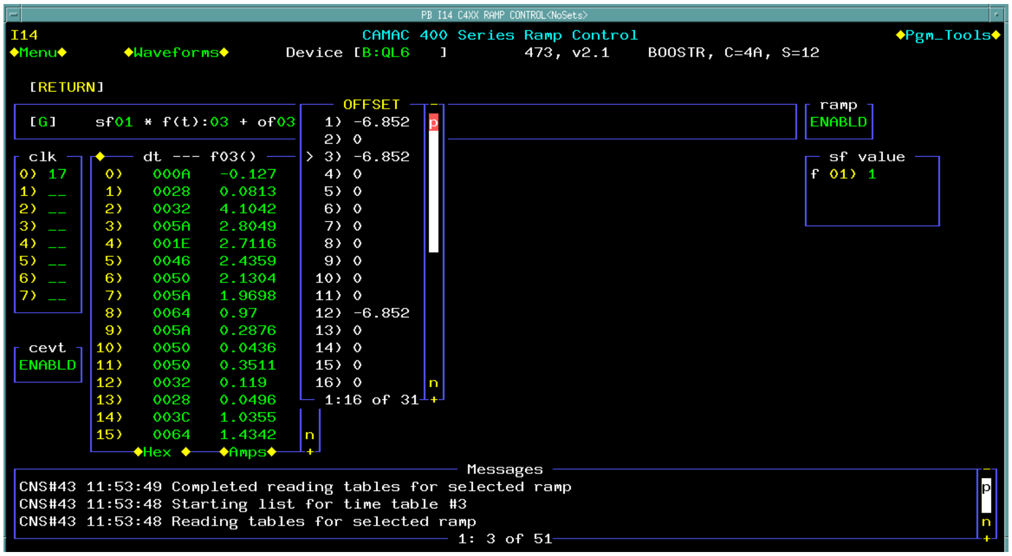
'Read Orbit Group' will read the current orbit and save it, so one can 'choose REF orbit' (select '601 turn' in the drop down menu) and subtract the saved orbit from the measured orbit and look at the difference. Click 'Repeat Orbit' to start measurement with looping



1.9 I14: change device setting: DC off set + ramp

- Type in device name under 'Device'

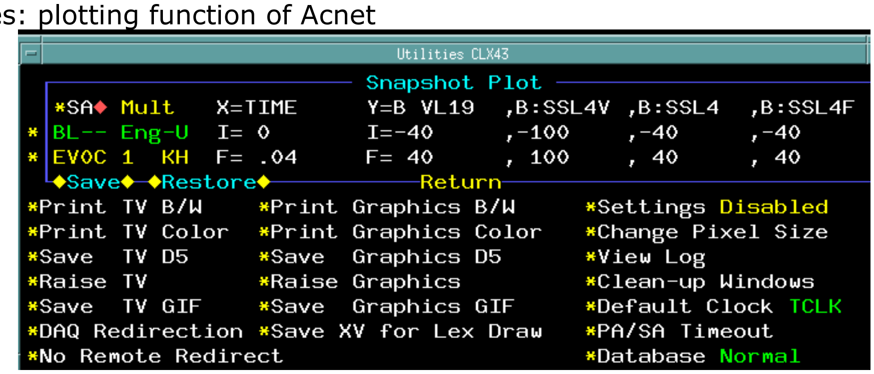




In the first figure, the 17 cycle offset is pointed at table entry 3 (see second figure). Now entry 3 is the same value as entry 1 (See ACL scripts automation). Entry 12 is changed during a demonstration of an ACL script. Entry 12 can be changed back to 0.

- Global device: can change all quadruple offset settings on 17 from entry 3 to entry 1. To change quad longs, go to menu-> global device -> family -> QL473, then select any device and change entry 03 to 01.

1.10 Utilities: plotting function of Acnet



- FTP (for longer period of time ~1s), SNP (for shorter period of time ~40ms, which is what this project often used).
- To create a plot that has slightly different need from the current plot, click on the red diamond, which will copy all your plot parameters to the next plot.

2 Theory [1]

2.1 Limitation of the single quad bump

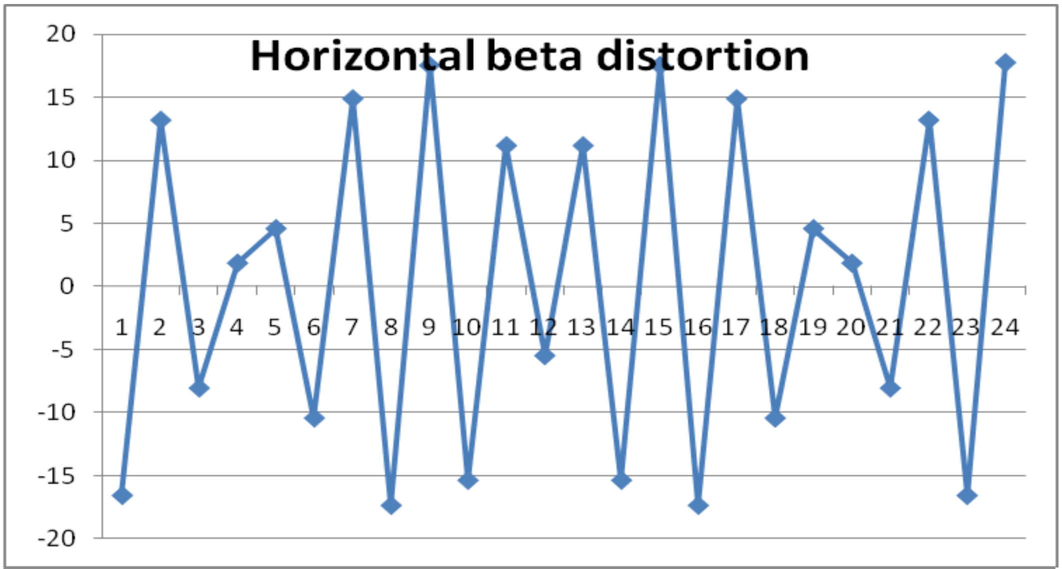
The close orbit β distortion caused by a single quad bump is [2]:

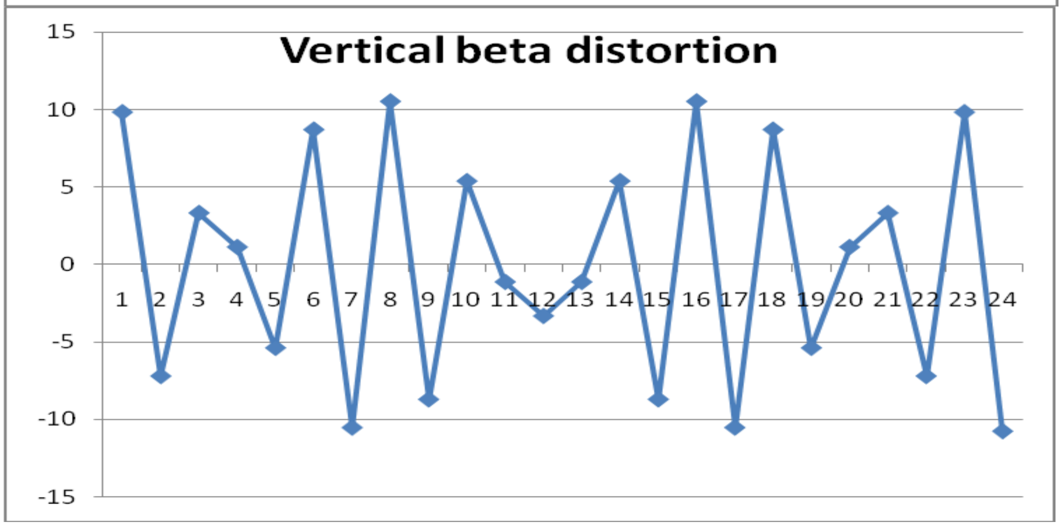
$$\frac{\Delta\beta(s)}{\beta(s)} = -q\frac{\beta_0}{2\sin 2\pi\nu}\cos\left[2\left(|\psi(s)| - \pi\nu\right)\right]$$

Let q=1, and given

	h-s	v-l
β (m)	33.7	20.5
v	6.7	6.8
Phase Advance/cell (μ) (rad)	1.754056	1.78023584

We can plot the beta distortion as a function of 24 periods in Booster





Note the horizontal and vertical distortion have opposite signs at the location of change (period 12).

Hence we can see if we only put in single quad bump as an attempt to correct local beta function, it will affect beta functions elsewhere and possibly increase beam loss.

In the main control room we've also found if we increase current on a quad, then loss is everywhere; if we decrease current then loss is localized.

The sign of the corrector quad is set up as such:

Horizontal plane: positive I, focus the beam on h plane, positive q, negative beta distortion;

Vertical plane: positive I, defocus the beam on v plane, negative q, negative beta distortion.

2.2 Multiple quad bumps **[1]**

We showed in above section that single quad bump is not the ideal method of correcting local beta function, we must then think of other method that will preserve beta function elsewhere through the cycle. There are 3, 4, and 5 quad bumps that we can put in (analogous to the 3 dipole bumps that will preserve the angular distortion elsewhere).

We can show mathematically 3-bump does not preserve the tune whereas the 4 and 5-bump do. The 4-bump is essentially to opposite direction 3-bump superimposed on each other (so tune shift cancel each other 1-1=0). The 5-bump is essentially a unit 3-bump with ½ sized opposite direction 3-bump superimposed on each side (so tune shift cancel each other 1-1/2-1/2=0).

We prefer bumps without tune shift since we want to avoid resonance. If tune shifts as the bump amplitude changes, the Booster operators will have a very hard time keeping track of the tune and keep it away from lower order rational and all orders of the machine RF resonance frequencies.

Between phase-preserving (tune shift=0) 4-bump and 5-bump, we numerically look for the one that can do a bigger change to the beta function given there is a max and min slew rate limit the corrector quad can ramp. From Bill Pellico we find that limit is ±30A.

2.3 Location of the quad bump

- Long vertical and short horizontal are the "high beta region", i.e. long section has maximum vertical beta, and short section has maximum horizontal beta. We want our bump to be between these two locations since we would want to do more beta change per ampere in the magnet.
- We choose near the collimator because at that location the aperture is best defined.
- We choose injection as opposed to extraction because near injection it allows for more beta change per unit current. But still it will be a very small change to the beam size that we are making. If we were to make change to beta later in the cycle, we need to enable individual ramp on the quads, which is not of our concern for now.

2.4 3-bump calculation

Given

Parameter	Value	
	Horizontal	Vertical
Kinetic Energy (injection)	.4 GeV	
Kinetic Energy extraction	8 GeV	

We can calculate Bρ for injection and extraction. Given B'L=0.0027*I,

$$q = \frac{B'L}{B\rho} = \frac{0.0027}{B\rho} * I$$

$$(pc)^2 = E^2 - (mc)^2 \qquad E + mc^2 = K + 2mc^2 = 0.4 + 0.938 \times 2$$

@ inj $\quad B\rho = \frac{(pc)\,GeV}{.3\,GeV}\ T\text{-}m = \frac{\sqrt{E^2-(mc^2)^2}}{.3\,GeV} = \frac{\sqrt{(0.4+0.938\times 2)0.4}}{.3}$

K=0.4 GeV $\qquad = 3.18$

$$q = \frac{0.0027}{B\rho} I = \frac{0.0027}{3.18} I = 8.49 \times 10^{-4} I \text{ on vertical plane}$$

@ extraction $\quad B\rho = \frac{\sqrt{(8+0.938\times 2)8}}{.3} = 29.6$

K=8GeV

$$q = \frac{0.0027}{B\rho} I = \frac{0.0027}{29.6} = 9.12 \times 10^{-5} I \text{ on vertical plane}$$

on horizontal plane $\quad q = -\frac{0.0027}{B\rho} I$

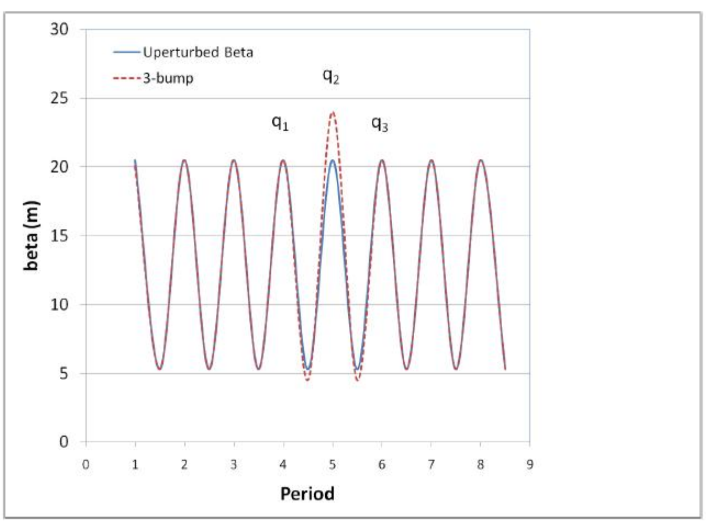


Figure 1: Schematic illustration of a localized β 3-bump.

$$
\begin{aligned}
q_2 &= 2\frac{\Delta\beta}{\beta^2}\cot 2\mu \\
q_1 = q_3 &= -\frac{\Delta\beta}{\beta^2}\frac{1}{\sin 2\mu} \\
\Delta\nu &= \frac{\Delta\beta}{2\pi\beta}\frac{\cos 2\mu - 1}{\sin 2\mu}
\end{aligned}
$$

mag strength per m beta distortion		l-h	l-v	s-h	s-v
3-bump	q2=	0.14002091	0.010689	0.004588	0.159917
	q1=q3=	0.07499135	0.00585	0.002457	0.087526
tune distortion per m beta distortion	Δv=	0.1407743	0.036525	0.025481	0.141276

Given

	h	v
β at long straight (β L) (m)	6.1	20.5
β at short straight (β S) (m)	33.7	5.3
Phase Advance/cell (μ) (rad)	1.754055898	1.78023584

We can calculate:

	Injection			
current per meter distortion	l-h	l-v	s-h	s-v
I1/1m	88.32314497	-6.8903667	2.893839	-103.086
I2/1m	164.9135187	-12.589326	5.403263	-188.347
I3/1m	88.32314497	-6.8903667	2.893839	-103.086

	Injection			
beta distortion per A	l-h	l-v	s-h	s-v
Δβ/1A	0.011322061	-0.1451302	0.345562	-0.0097
Δβ/1A	0.006063784	-0.0794324	0.185073	-0.00531
Δβ/1A	0.011322061	-0.1451302	0.345562	-0.0097

Extraction				
	l-h	l-v	s-h	s-v
I1/1m	822.1273856	-64.136746	26.93636	-959.54
I2/1m	1535.04407	-117.18367	50.29453	-1753.17
I3/1m	822.1273856	-64.136746	26.93636	-959.54

Extraction				
beta distortion per A	l-h	l-v	s-h	s-v
Δβ/1A	0.001216357	-0.0155917	0.037125	-0.00104
Δβ/1A	0.000651447	-0.0085336	0.019883	-0.00057
Δβ/1A	0.001216357	-0.0155917	0.037125	-0.00104

tune distortion per A in I2	l-h	l-v	s-h	s-v
Δv/1A	0.001593855	-0.0053009	0.008805	-0.00137
tune distortion of 15A on I2	0.023907827	-0.0795135	0.132081	-0.02056
tune distortion of 30A on I2	0.047815655	-0.1590269	0.264162	-0.04111

This calculation of tune shift is smaller than what was experimentally found in **Section 3.3**. It could be due to beta distortion, phase advance shift/tune shift.

2.5 4-bump calculation

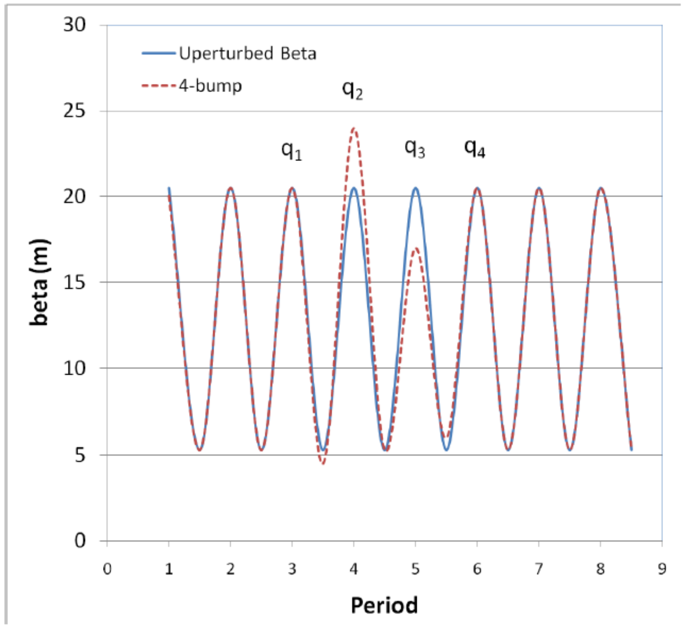


Figure 2: Schematic illustration of a localized β 4-bump which preserves the overall phase advance.

$$
\begin{aligned}
q_1 &= -\frac{\Delta\beta}{\beta^2}\frac{1}{\sin 2\mu} \\
q_2 &= \frac{\Delta\beta}{\beta^2}\left(2\cot 2\mu + \frac{1}{\sin 2\mu}\right) \\
q_3 &= -q_2 \\
q_4 &= -q_1
\end{aligned}
$$

mag strength per m beta distortion		l-h	l-v	s-h	s-v
4-bump	q1=	0.074991	0.00585	0.002457	0.087526
	q2=	0.06503	0.004839	0.002131	0.072392
	q3=	-0.06503	-0.00484	-0.00213	-0.07239
	q4=	-0.07499	-0.00585	-0.00246	-0.08753

Injection				
current per meter distortion	l-h	l-v	s-h	s-v
I1/1m	88.32314	-6.89037	2.893839	-103.086
I2/1m	76.59037	-5.69896	2.509424	-85.2612
I3/1m	-76.5904	5.69896	-2.50942	85.26122
I4/1m	-88.3231	6.890367	-2.89384	103.0857

Injection				
beta distortion per A	l-h	l-v	s-h	s-v
Δβ_1/1A	0.011322	-0.14513	0.345562	-0.0097
Δβ_2/1A	0.013056	-0.17547	0.398498	-0.01173
Δβ_3/1A	-0.01306	0.175471	-0.3985	0.011729
Δβ_4/1A	-0.01132	0.14513	-0.34556	0.009701

Extraction				
current per meter distortion	l-h	l-v	s-h	s-v
I1/1m	822.1274	-64.1367	26.93636	-959.54
I2/1m	712.9167	-53.0469	23.35816	-793.626
I3/1m	-712.917	53.04692	-23.3582	793.6265
I4/1m	-822.127	64.13675	-26.9364	959.5396

Extraction				
beta distortion per A	l-h	l-v	s-h	s-v
Δβ_1/1A	0.001216	-0.01559	0.037125	-0.00104
Δβ_2/1A	0.001403	-0.01885	0.042812	-0.00126
Δβ_3/1A	-0.0014	0.018851	-0.04281	0.00126
Δβ_4/1A	-0.00122	0.015592	-0.03712	0.001042

current ratio per beta distortion	l-h	l-v	s-h	s-v
I1/I2	1.153189	1.209057	1.153189	1.209057
I1/I3	-1.15319	-1.20906	-1.15319	-1.20906
I1/I4	-1	-1	-1	-1

2.6 5-bump calculation

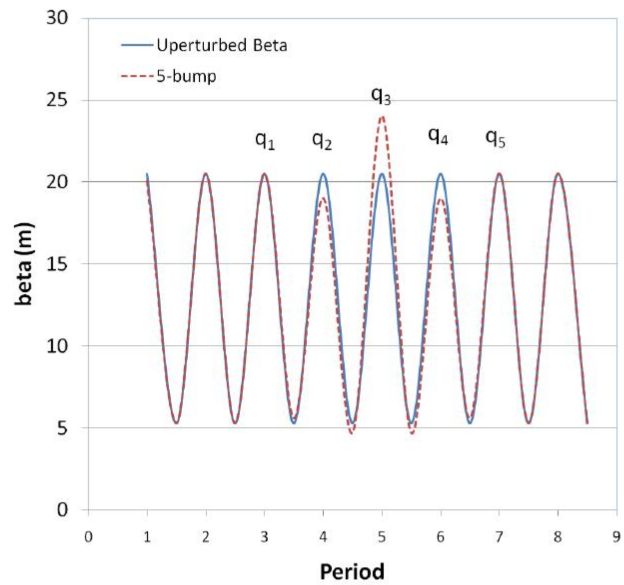


Figure 3: Schematic illustration of a localized β 5-bump which preserves the overall phase advance.

$$
\begin{aligned}
q_1 &= \frac{1}{2}\frac{\Delta\beta}{\beta^2}\frac{1}{\sin 2\mu} \\
q_2 &= -\frac{\Delta\beta}{\beta^2}\left(\cot 2\mu + \frac{1}{\sin 2\mu}\right) \\
q_3 &= \frac{\Delta\beta}{\beta^2}\left(2\cot 2\mu + \frac{1}{2}\frac{1}{\sin 2\mu}\right) \\
q_4 &= q_2 \\
q_5 &= q_1
\end{aligned}
$$

mag strength per m beta distortion		l-h	l-v	s-h	s-v
5-bump	q1=	-0.037496	-0.00293	-0.00123	-0.04376
	q2=	0.0049809	0.000506	0.000163	0.007567
	q3=	0.1025252	0.009078	0.003359	0.116154
	q4=	0.0049809	0.000506	0.000163	0.007567
	q5=	-0.037496	-0.00293	-0.00123	-0.04376

Injection				
current per meter distortion	l-h	l-v	s-h	s-v
I1/1m	-44.161572	3.4451833	-1.44692	51.54284
I2/1m	5.8663856	-0.595703	0.192208	-8.91222
I3/1m	120.75195	-10.69168	3.956344	-136.804
I4/1m	5.8663856	-0.595703	0.192208	-8.91222

I5/1m	-44.161572	3.4451833	-1.44692	51.54284

Injection				
	l-h	l-v	s-h	s-v
Δβ_1/1A	-0.0226441	0.2902603	-0.69112	0.019401
Δβ_2/1A	0.1704627	-1.678687	5.202709	-0.11221
Δβ_3/1A	0.0082814	-0.093531	0.252759	-0.00731
Δβ_4/1A	0.1704627	-1.678687	5.202709	-0.11221
Δβ_5/1A	-0.0226441	0.2902603	-0.69112	0.019401

Extraction				
	l-h	l-v	s-h	s-v
I1/1m	-411.06369	32.068373	-13.4682	479.7698
I2/1m	54.60535	-5.544913	1.789102	-82.9566
I3/1m	1123.9804	-99.52007	36.82634	-1273.4
I4/1m	54.60535	-5.544913	1.789102	-82.9566
I5/1m	-411.06369	32.068373	-13.4682	479.7698

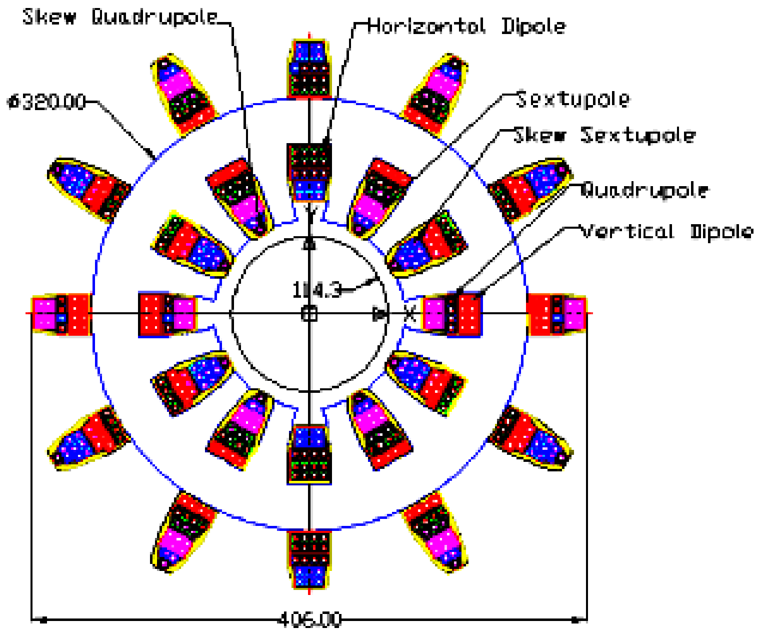
Extraction				
beta distortion per A	l-h	l-v	s-h	s-v
Δβ_1/1A	-0.0024327	0.0311834	-0.07425	0.002084
Δβ_2/1A	0.0183132	-0.180345	0.55894	-0.01205
Δβ_3/1A	0.0008897	-0.010048	0.027154	-0.00079
Δβ_4/1A	0.0183132	-0.180345	0.55894	-0.01205
Δβ_5/1A	-0.0024327	0.0311834	-0.07425	0.002084

current ratio per beta distortion	l-h	l-v	s-h	s-v
I1/I2	-7.5279014	-5.783386	-7.5279	-5.78339
I1/I3	-0.3657214	-0.32223	-0.36572	-0.37676
I1/I4	-7.5279014	-5.783386	-7.5279	-5.78339
I1/I5	1	1	1	1

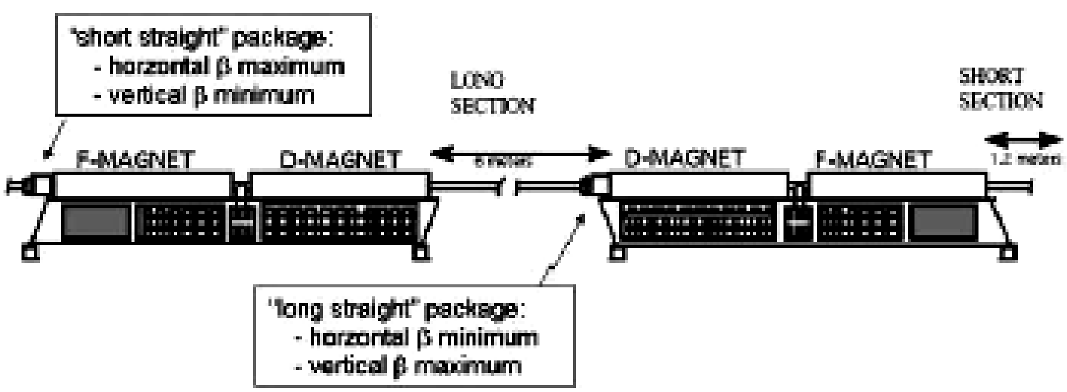
3 Experiment

3.1 Correction magnet package

48 total were installed 2007 and 2008, including horizontal and vertical dipoles, normal and skew quadrupoles, and normal and skew sextupoles, to provide control up to the extraction energy (8GeV). The multiple elements are put together as such **[3]**:



They are located at **[4]**:



3.2 Find dipole compensations

- Because beam does not necessarily go through the center of the quadruple, when we ramp up the quadruple strength we will see an angular kick to the beam at the location of a quadruple bump. That is the steering error. We want to rid of this error since this might affect the result of aperture scan that we will do later to find out the size of the beam. And the steering error might also cause the beam to scrape the pipe and causes beam loss.
- To compensate these steering errors, we put in single quad bump of ±30A on QL4 through 8, and try to correct the steering error on the BPM plot by trying different H and V dipole values by hand.

  The dipole compensation values are given here, also see **Appendix B - dipole compensation** for BPM plot before and after the dipole compensations are added in:

QL4	-31.28	28.17
VL4	0.38	-0.43
HL4	0.17	-0.5

QL5	-31.58	28.42
VL5	-0.47	0.47
HL5	1.17	-1.17

QL6	-36.85	23.15
VL6	0.12	-0.1
HL6	0.5	-0.5

QL7	-30.47	29.53
VL7	0.046	0
HL7	0.245	-0.5

QL8	-30.18	29.82
VL8	0.25	-0.26
HL8	0.54	-0.67

- We hence obtain the dipole ratio by dividing the dipole value with the change in quadruple values. Combine that with the calculated quadruple ratios, we can then obtain the ratios for 9mult (3-bump), 12mult (4-bump), 15mult (5-bump).
- Here are the calculated ratios for 9, 12 mult, they are put in B111 page as they are:

q5	1
v5	0.015667
h5	-0.039
q6	1.827091
v6	-0.0067
h6	-0.03045
q7	1
v7	-0.00153
h7	-0.01242

q5	1
v5	0.015667
h5	-0.039
q6	0.827091
v6	-0.00303
h6	-0.01378
q7	-0.82709
v7	0.001268
h7	0.01027
q8	-1

v8	0.0085
h8	0.020167

- Here is the calculated ratios for 15 mult,

q4	1
v4	-0.0135
h4	-0.01117
q5	-0.17291
v5	-0.00271
h5	0.006743
q6	-3.10337
v6	0.011379
h6	0.051723
q7	-0.17291
v7	0.000265
h7	0.002147
q8	1
v8	-0.0085
h8	-0.02017

However when I put them in there still exist a steering error that is a bit more than 1mm, so I went tried some other dipole values. The finally settled ratio for the 15 mult (5-bump) is shown in graph under **Section 1.3** “Page 16”, where v4 was originally calculated to be -.0135, v6=.025826, h6=.098244, v7=0.000265. After this change the steering error for 5-bump is corrected.

Also see **Appendix C- with and without dipole compensation for 5bump** for effect of the dipole compensation.

We can also calculate the maximum steering error:

Calculation of quad steering:

The max distortion caused by a quad steering is:

$$\Delta X_{max} = \frac{\theta\sqrt{\beta_s \beta_2}}{2\sin(\mu\pi)}$$

$$\theta = \frac{\Delta B' L}{B\rho} \overset{inj}{=} \frac{0.0027}{3.18} I$$

let $I = 1$

at horizontal quad

$$\Delta X_{max} = \frac{\frac{0.0027}{3.18}\sqrt{6.1 \times 33.7}}{2\sin(\pi \times 1.754)} = \sim 0.0087[illegible]18 \text{ m}$$

$$= 8.72\text{mm per A}.$$

Experimentally we found. $\sim$ 1mm per A.

This discrepancy could be due to beta distortion.

3.3 Tune measurement of 3, 4, 5-bumps

Detail of measurement method see **Section 1.6** and **1.7** (or for Meghan's original instruction see **Appendix D - Instructions for Booster Beta Function Measurement Studies**)

Set the program to export a data file containing the spectra, the data files can be found at http://www-bd.fnal.gov/userb/booster/. Need to be on Fermilab's network to be able to access this site.

All data files from tune measurements can be found in **Appendix E - Tune measurement for 3, 4, and 5bumps**.

To test our theoretical calculation with regard to the 3 kinds of quad bumps, we put in ±15 and ±30 quad bumps for 3, 4, 5-bump and look at the transmission (integrated charge, i.e. the last value at the end of the cycle in IRMCHG (before it drops to zero)) as well as the tune (finding the highest point of the spectrum will give you a pretty accurate value, within 0.0001). Here are the data and plots.

Note: he Fourier Transform only gives the fractional tune. Add 6 to get the real tune. Plot below uses only the fractional tune to enlarge change.

Zero (no quad bump)

Tune	zero avg
1	0.871823
2	0.871746
3	0.850323
4	0.850628
5	0.85004
6	0.852728
Avg	0.857881

chg0	zero avg
1	1.363995
2	1.353777
3	1.338452
4	1.318017
5	1.358886
avg	1.346625

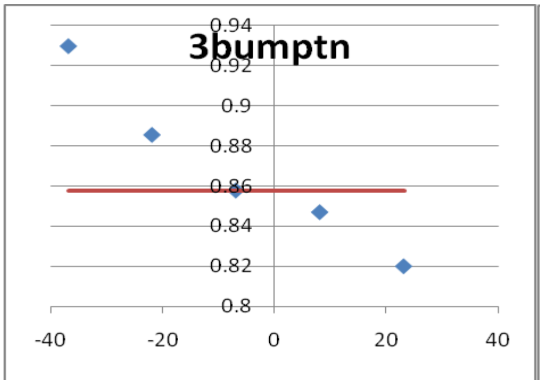
Quad bumps

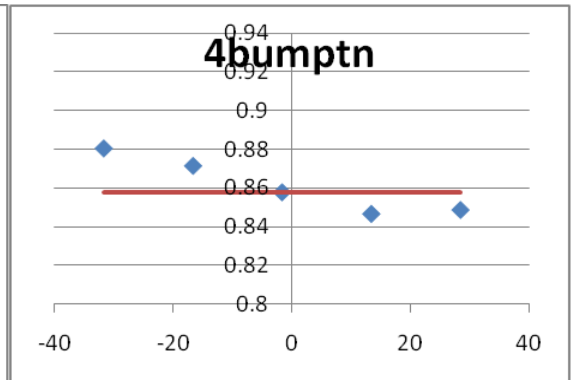
3bump	current on QL6	int charge	tune (97 turns)
+30	23.19	1.1596508	0.820141
+15	8.165	1.28225708	0.847103
0	-6.852	1.34662537	0.857881333
-15	-21.87	1.2669313	0.885641
-30	-36.83	0.99106723	0.92983

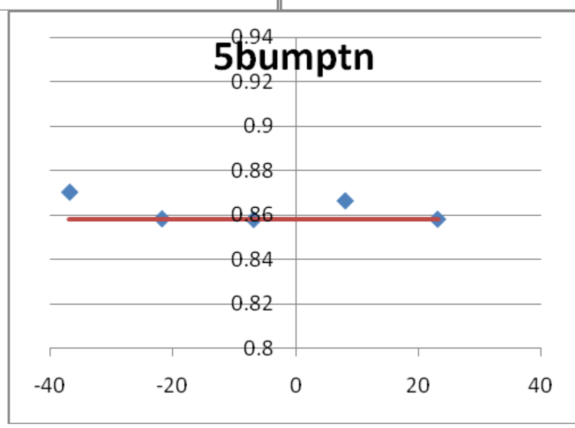
4bump	current on QL5	int charge	tune (97 turns)
+30	28.45	1.27203989	0.848745
+15	13.44	1.32823443	0.846715
0	-1.577	1.34662537	0.857881333
-15	-16.56	1.30269146	0.871515
-30	-31.6	1.22606254	0.880545

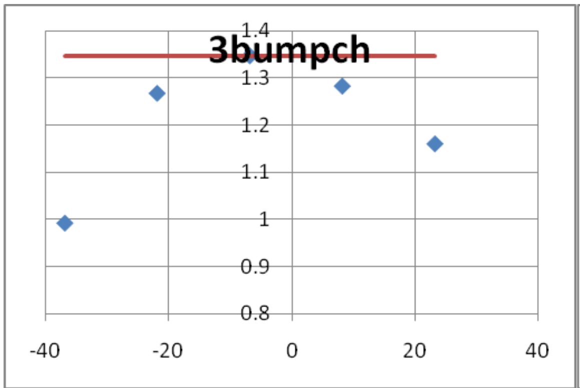
5bump	current on QL6	int charge	tune (97 turns)
+30	23.19	1.29758286	0.858029
+15	8.119	1.30780005	0.866246
0	-6.852	1.34662537	0.857881333
-15	-21.82	1.33845162	0.858218
-30	-36.89	1.25160551	0.870136

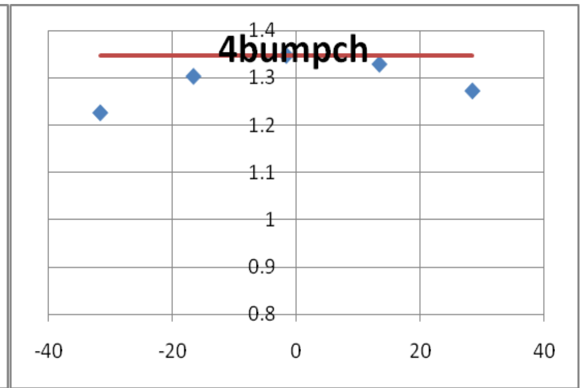
Red lines show where the quiescent tune and integrated charge should be. We can observe that 5-bump has the most stable tune, and the 3-bump has more significant beam loss at extreme.

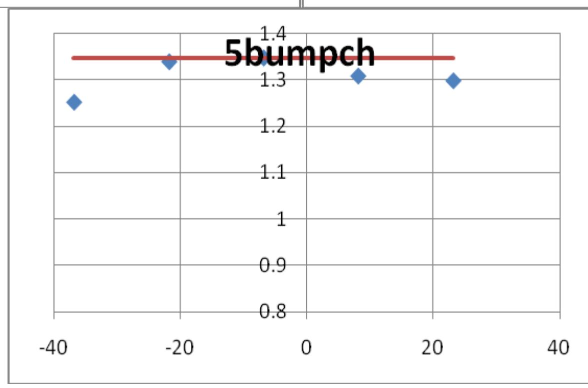







3bumpch
1.4
1.3
1.2
1.1
1
0.9
0.8
-40
-20
0
20
40


4bumpch
1.4
1.3
1.2
1.1
1
0.9
0.8
-40
-20
0
20
40


5bumpch
1.4
1.3
1.2
1.1
1
0.9
0.8
-40
-20
0
20
40

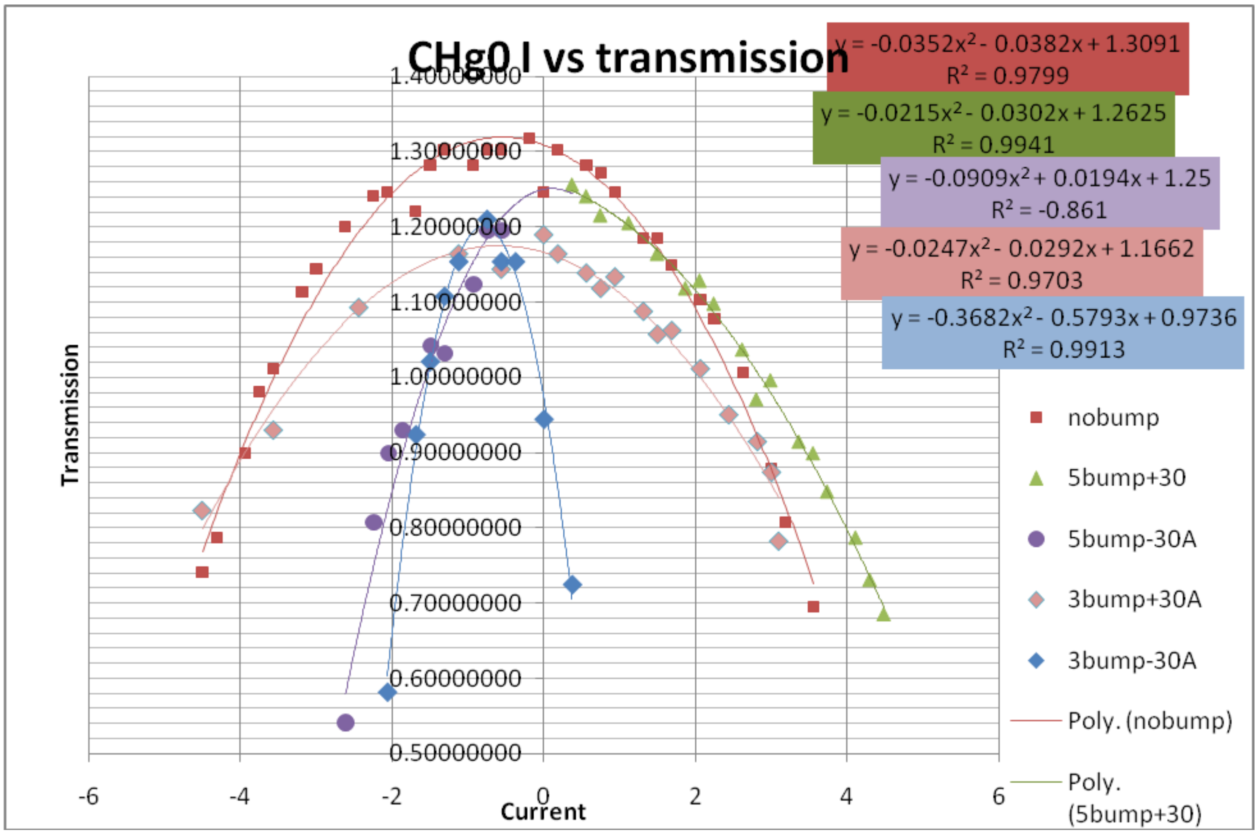
3.4 Aperture Scan – transmission

- aperture scan setup: dipole 3-bump

VL5*9.6
VL6*2.6
VL7*9.6

This vertical dipole bump will move the beam up and down in the beam pipe. So by looking at position of the beam vs. the transmission, we get an idea of the size of the beam. For example, if the beam is bigger, then the transmission will be reduced sooner because the beam will scrape the pipe sooner when moving the beam up and down.

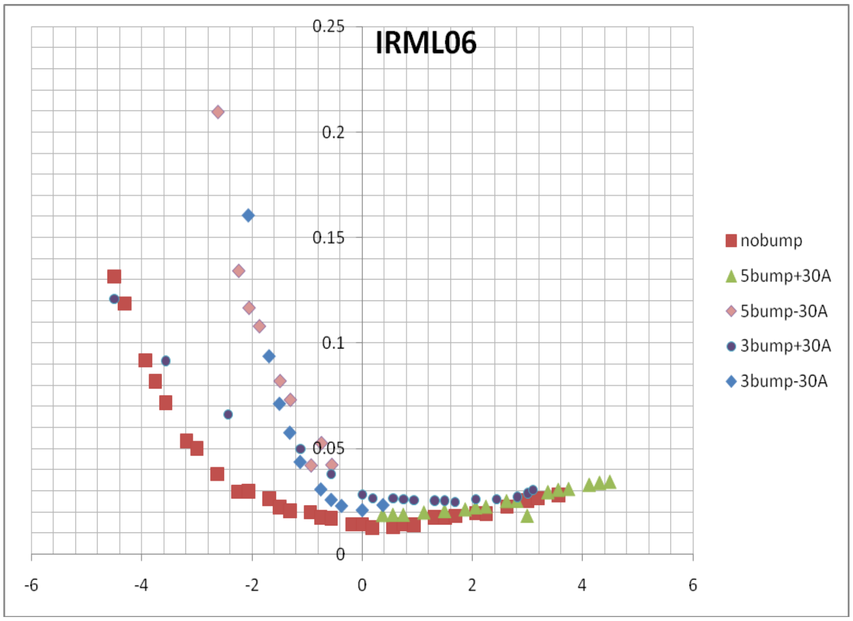
- Due to time limit, we only tested 3 and 5-bump. We looked at integrated charge (CHg0), beam loss monitor at long 6 (IRML06), and two other loss monitors in long 6 (IRM061 and IRM062). Data is all taken from B136.
- L06: downstream of the long straight 6,
  061: in front of the combine function magnet,
  062: between L06 061,
  All are located at the tap of the beam pipe.

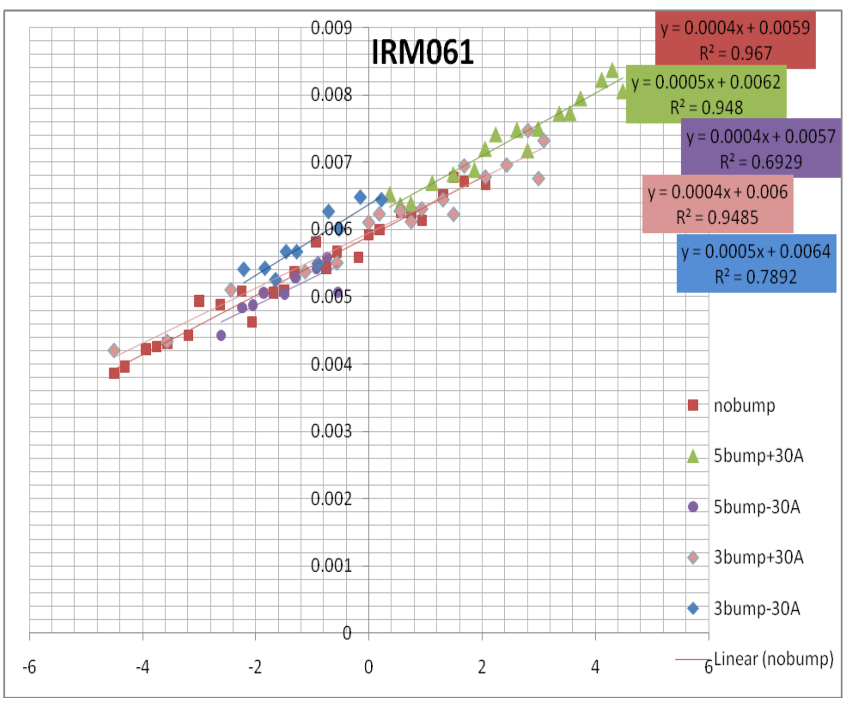


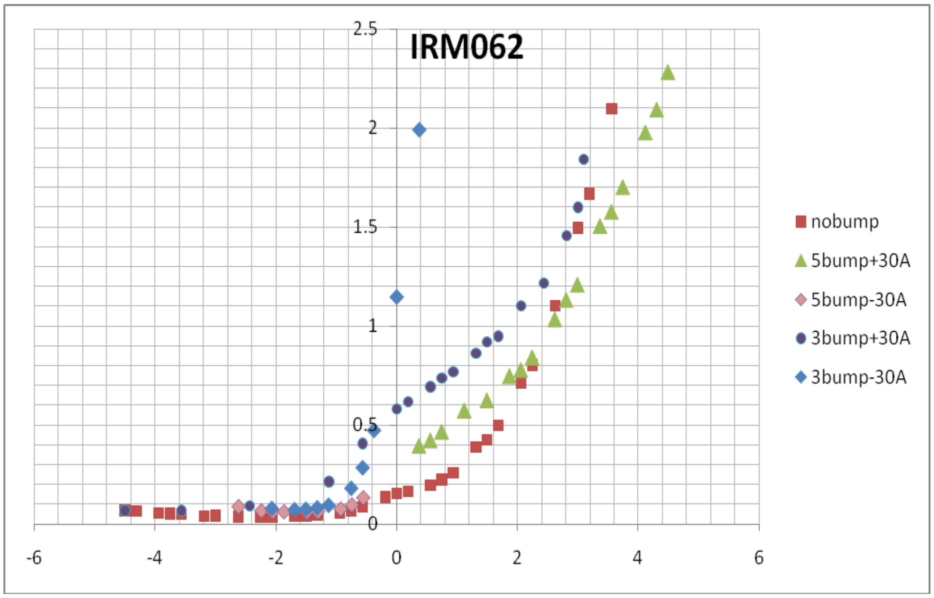
We can calculate the FWHM by solving y(x)-0.5*y_max=0, where y(x) is the best quadratic fit shown in above graph. FWHM will give us some measure of the size. The shape actually should be like quadratic but rather with a flat top, however, at injection the beam usually has a wide spread and hence resulting in like-quadratic shape. We fit it as quadratic only to claculate its FWHM.

	ymax	FWHM
nobump	1.31946	8.65849

5bp+	1.27311	10.88198
5bp-	1.25104	6.11425
3bp+	1.17483	9.75376
3bp-	1.20146	2.554855



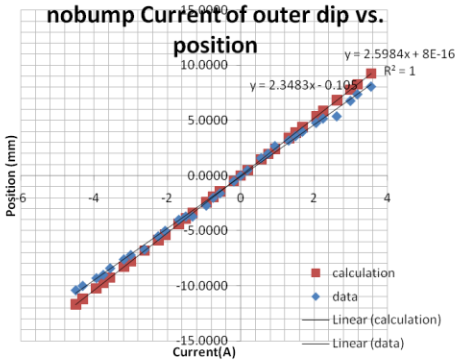


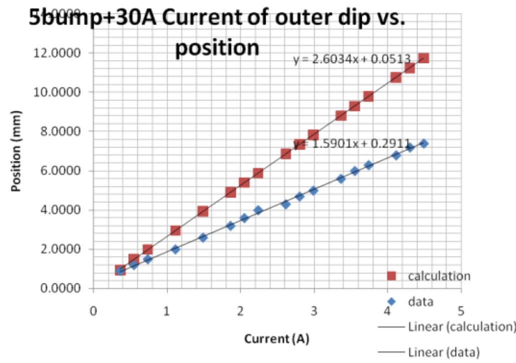


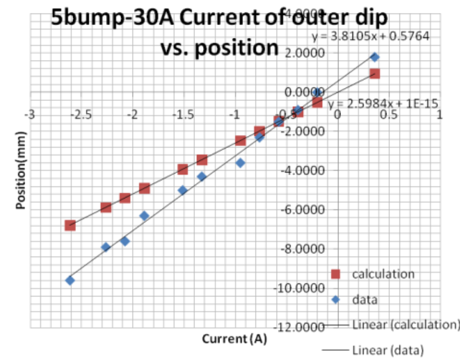
For all the data, see **Appendix F - Aperture scan transmission CHg0, IRML06, IRM061, IRM062**.

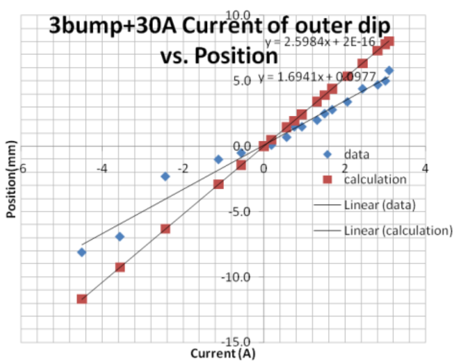
3.5 Aperture Scan – current vs. position

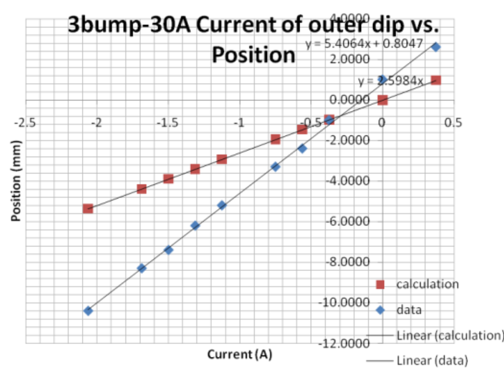
- Data is obtained from B40 Booster Orbit. The amplitude of dipole bump around period 6 is read to one decimal. All images see **Appendix G - BPM images for aperture scan.**
- Calculation: $\Delta x=\Delta\theta*\beta_L*\mathrm{Sin}\mu_L$, where $\Delta\theta = k\Delta I/(B\rho \text{ at } 400\mathrm{MeV})$
  Given k =.0157/38.1=0.000412073 (T-m/A) **[5]**
  And $B\rho$ (at 400MeV) = 3.18 (**Section 2.4**)
  We can also calculate the position of the bump from the current. The line is given in read. Data taken is given in blue.









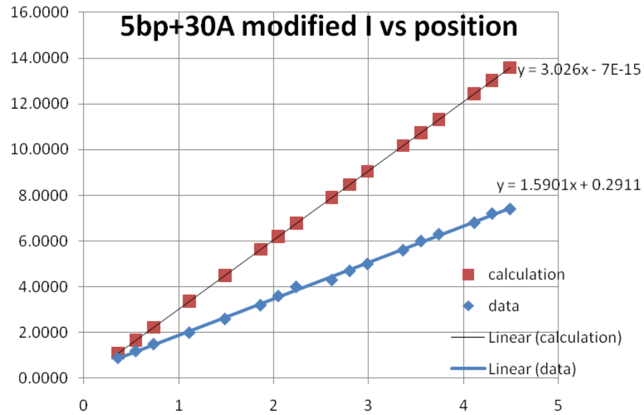


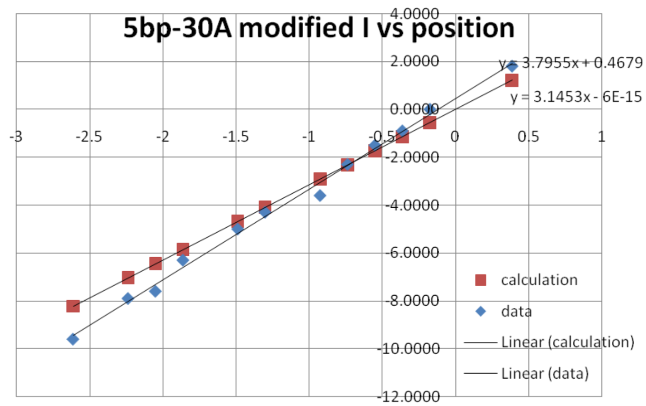
Observe the systematic discrepancy between the calculations and obtained data, this is because we didn't take into the account that beta function is not constant at the location because of the quad bumps we inserted. Details about data and calculation see **Appendix H - current vs. position**.

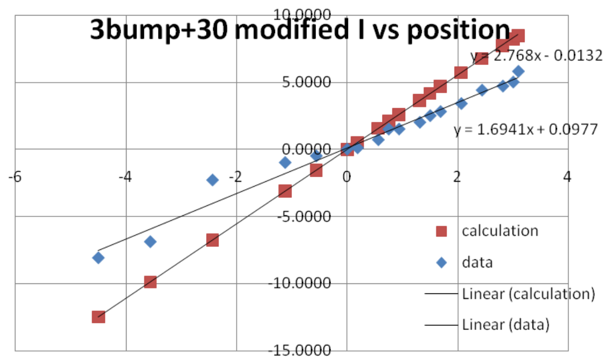
So the modified position change is in fact:

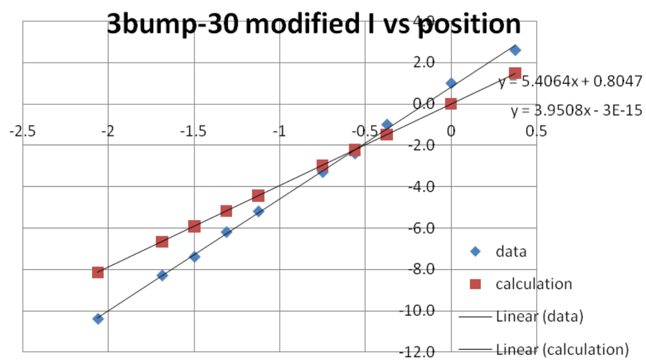
$$\Delta x = \frac{1}{2\sin\pi\nu}\left(\Delta\theta_C\beta_C\cos\pi\nu + 2\Delta\theta_{L,R}\sqrt{\beta_C\beta_{L,R}}\cos(\mu-\pi\nu)\right) \quad \textbf{[6]}$$

And we obtained a new calculation:





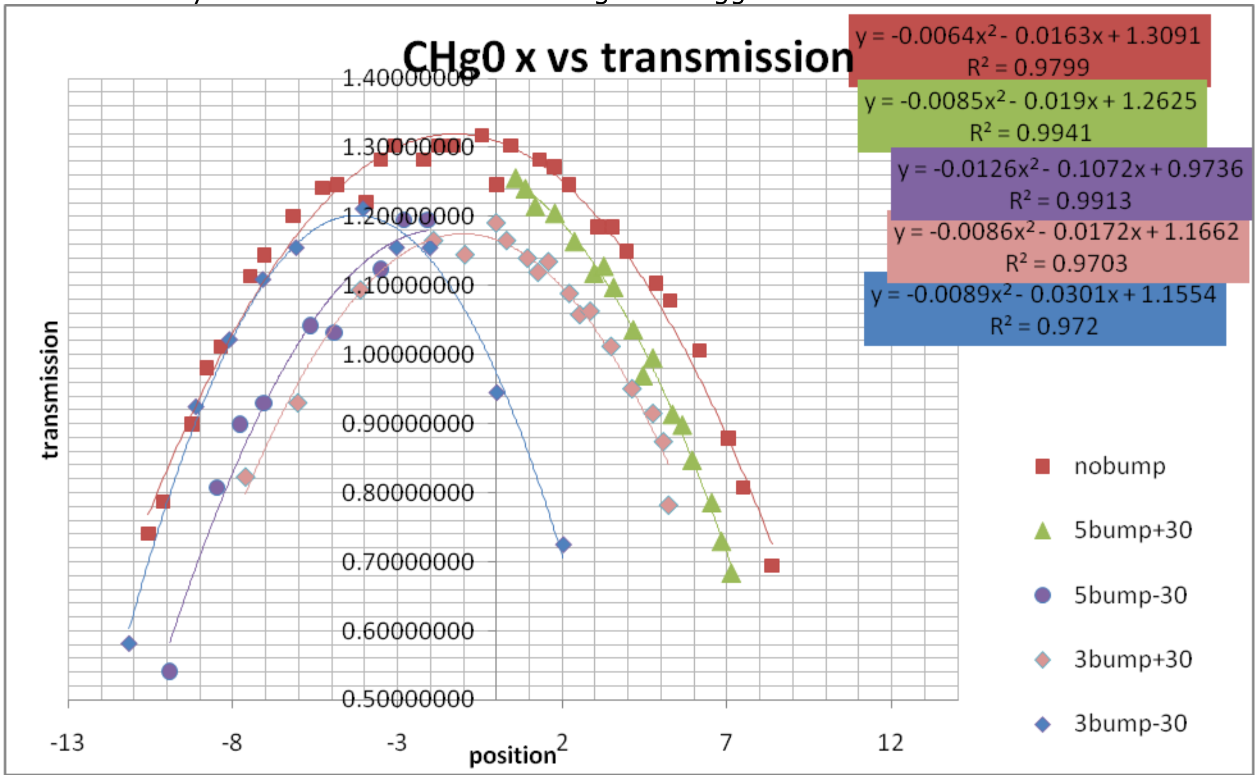




We can see the improvements on 5bump-30A, and both 3bump cases, curiously 5bump+30A has gotten worse.

3.6 Position vs. Transmission and beam size

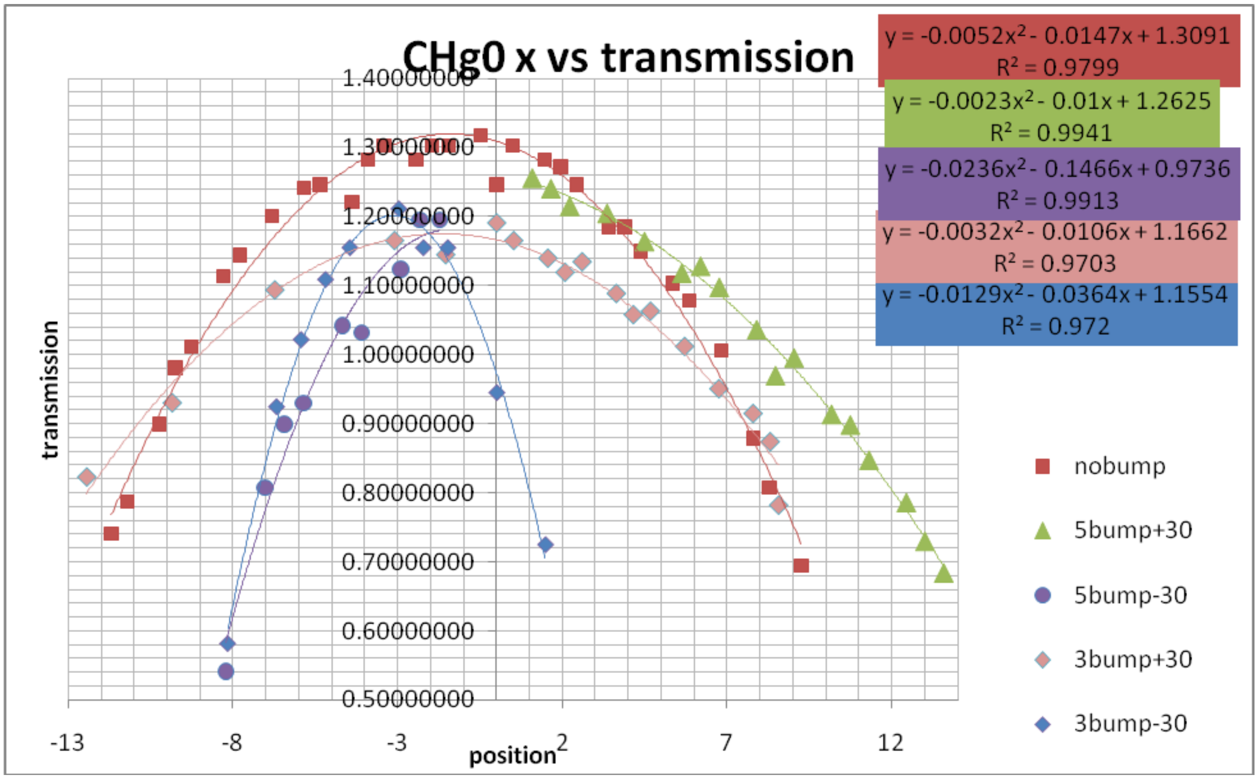
Using the data slope of current vs. position, we get this result, which basically says in every situation the beam size has gotten bigger:



With FWHM

	ymax	FWHM
nobump	1.31946	20.3061
5bp+	1.27312	17.30772
5bp-	1.20156	16.28986
3bp+	1.1748	16.52904
3bp-	1.20161	13.81062

However we find if we use the calculated slope of position vs. current, we will get a result that make much better sense. By turning up current, we create negative beta distortion therefore reduced beam size, by turning down current, we create positive beta distortion therefore increased beam size.



With FWHM:

	ymax	FWHM
nobump	1.31949	22.52767
5bp+	1.27337	33.2758
5bp-	1.20126	10.0897
3bp+	1.17498	27.0991
3bp-	1.18108	13.53192

The quiescent beam size seems to be consistent with calculation:

beam size at injection.

$$\varepsilon = \sqrt{\frac{12\pi \text{ mm-mr} \times \beta(t)}{6\gamma\beta}}$$

$$\beta\gamma = \frac{\beta\gamma c m}{mc} = \frac{pc}{mc^2/c} = \frac{\sqrt{(0.4+0.938\times 250.4)}}{0.938\times 10^9/3\times 10^8} = 0.305165$$

$$\varepsilon = \sqrt{\frac{12\times\pi\times 10^{-6}\times 20.5}{6\times 0.305165}} = 0.02055\text{ m} \doteq 20.55\text{ mm}$$

compared to what we found : 20.3061mm (FWHM using slope of current vs. position dat

~~2.7~~

22.52767mm (FWHM using slope of calcula. current vs. position)

So the effect of the mults on beam size is inconclusive. Some future experiments/questions include:

- Measurement of beta function, proving the beta function indeed is preserved elsewhere.
- Answering the question: does beam frequency (phase advance) change within the mult bumps that might have impact on the beta change? And might that explain the discrepancy between the calculated aperture scan position and the data?

4 ACL scripts and automation

4.1 Quad offset

Goal: want to be able to separate 17 cycle settings from the rest of the cycles by pointing 17 cycle devices to a separate table entry. This process will be tedious by hand, so we automate the process using ACL (Accelerator (ACNET) Command Language).

By brute force, Duane Newhart had written two scripts that will copy from table entry 1 to entry 12, and can be called from any page.

To access the scripts, go to any page click on upper right hand corner 'PTools' ->'ACL Edit/Run'. In 'ACL edit window', 'Action'->'Read File'-> 'Text file' -> 'Browse' -> QL[0]toQL[11]. Here is the script.

```
copy B_QL1O [0_0] to B_QL1O [11_11]
copy B_QL2O [0_0] to B_QL2O [11_11]
copy B_QL3O [0_0] to B_QL3O [11_11]
copy B_QL4O [0_0] to B_QL4O [11_11]
copy B_QL5O [0_0] to B_QL5O [11_11]
copy B_QL6O [0_0] to B_QL6O [11_11]
copy B_QL7O [0_0] to B_QL7O [11_11]
copy B_QL8O [0_0] to B_QL8O [11_11]
copy B_QL9O [0_0] to B_QL9O [11_11]
copy B_QL10O [0_0] to B_QL10O [11_11]
copy B_QL11O [0_0] to B_QL11O [11_11]
copy B_QL12O [0_0] to B_QL12O [11_11]
copy B_QL13O [0_0] to B_QL13O [11_11]
copy B_QL14O [0_0] to B_QL14O [11_11]
copy B_QL15O [0_0] to B_QL15O [11_11]
copy B_QL16O [0_0] to B_QL16O [11_11]
copy B_QL17O [0_0] to B_QL17O [11_11]
copy B_QL18O [0_0] to B_QL18O [11_11]
copy B_QL19O [0_0] to B_QL19O [11_11]
copy B_QL20O [0_0] to B_QL20O [11_11]
copy B_QL21O [0_0] to B_QL21O [11_11]
copy B_QL22O [0_0] to B_QL22O [11_11]
copy B_QL23O [0_0] to B_QL23O [11_11]
copy B_QL24O [0_0] to B_QL24O [11_11]
```

And same way there is an analogous script for short quads:

```
copy B_QS1O [0_0] to B_QS1O [11_11]
copy B_QS2O [0_0] to B_QS2O [11_11]
copy B_QS3O [0_0] to B_QS3O [11_11]
copy B_QS4O [0_0] to B_QS4O [11_11]
copy B_QS5O [0_0] to B_QS5O [11_11]
copy B_QS6O [0_0] to B_QS6O [11_11]
copy B_QS7O [0_0] to B_QS7O [11_11]
copy B_QS8O [0_0] to B_QS8O [11_11]
copy B_QS9O [0_0] to B_QS9O [11_11]
copy B_QS10O [0_0] to B_QS10O [11_11]
copy B_QS11O [0_0] to B_QS11O [11_11]
copy B_QS12O [0_0] to B_QS12O [11_11]
copy B_QS13O [0_0] to B_QS13O [11_11]
copy B_QS14O [0_0] to B_QS14O [11_11]
copy B_QS15O [0_0] to B_QS15O [11_11]
```

```
copy B_QS16O [0_0] to B_QS16O [11_11]
copy B_QS17O [0_0] to B_QS17O [11_11]
copy B_QS18O [0_0] to B_QS18O [11_11]
copy B_QS19O [0_0] to B_QS19O [11_11]
copy B_QS20O [0_0] to B_QS20O [11_11]
copy B_QS21O [0_0] to B_QS21O [11_11]
copy B_QS22O [0_0] to B_QS22O [11_11]
copy B_QS23O [0_0] to B_QS23O [11_11]
copy B_QS24O [0_0] to B_QS24O [11_11]
```

Note: to call table entry must use range [xx_xx].

Brian Hendricks has helped me come up with a better way that can do exactly the same thing:

```
host_request WINDOW_HEIGHT=large

declare val double                # variable to hold setting value

loop 5 count=4                    # loop over the number of devices to copy
  base = 'B:QL' + toString(count)
  base += 'O'                     # specify offset device
  print base
  void deviceSpec(base,g:cdv0)
  val = g:cdv0.set[0]             # read value of element 0
  print 'Setting = ' val
  set g:cdv0.set[2] = val
endloop
```

"O" means the offset of a device. "D" would mean "DAQ", "T" would mean ramp. About virtual devices please see section **4.2**. This script can copy values from entry 1 to entry 3 from quad long 4 to quad long 8. This script is saved in the datafile on Acnet as "BoosterQLOffsetCopy".

4.2 Enabling dipoles: copy dac values to ramp values

Brian Hendricks came up with a flexible way to set the ramp values to dac values before enabling the dipoles, using virtual devices. There are total 100 virtual devices, and they look like "g:cdv#". The following script put in plain words: we create an array that can hold values that the real device dac values (call them dac_device) through a virtual device offset (g:cdv0.set) can be copied to, and which process will loop over 5 real device names (b:hlxxd) (the virtual devices are used 5 times). Then read the real devices ramp values (b:hlxxt) into another virtual device g:cdv1, and use another loop to copy these ramp values to the next 5 entries on the array. Then finally set the virtual device table equal to the array, which means the real devices are point to the array values as well.

```
host_request WINDOW_HEIGHT=large

declare val double[6]             # array to hold setting values

loop 5 count=4                    # loop over the number of devices to copy
   base = "b:hl" + toString(count)
   dac_device = base + "d"
```

```
   print dac_device
   void deviceSpec(dac_device,g:cdv0)
   val[0] = g:cdv0.set             # copy reading value into element 0 of setting array
   loop 5 cntr2=1      # fill the rest of the setting array with the same value
   val[cntr2] = val[0]
   endloop
   device = base + "t"
   print device
   void deviceSpec(device,g:cdv1)
   print 'Setting = ' val[0]
   set g:cdv1[0:5] = val          # set first 6 elements of output device
endloop
```

Note: All scripts in this section have been successfully carried out in MCR.

5 Conclusion

We have learned through this project that the steering errors due to quad bumps can be compensated by dipoles on each plane. We have also seen the tune shift and transmission quality of the different quad bumps similar to what we predicted. The eventual beam size change is inconclusive. We would need to confirm our method through future beta measurement. And through the development of some simple ACL scripts, our future work in cycle 17 based on changing corrector magnets setting is made easier.

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Bibliography

[1] Eric Prebys, "Quad β Bumps and Phase Conserving Mults", June 25, 2010, Private Communication
[2] For a more rigorous calculation, see G. Dugan, "USPAS Lecture 8" (2001), http://www.lns.cornell.edu/~dugan/USPAS/Lect8.pdf
[3] V.S. Kashikhin, et al., "A New Correction Magnet Package for the Fermilab Booster Synchrotron," PAC'05, May 2005
[4] E.J. Prebys, et al., "New corrector system for the Fermilab Booster", PAC'07.
[5] Eric Prebys, Jim Lackey, Dave Harding, Craig Drenna, "Booster Corrector System Specification" Table VI, revised 20 July 2006 http://beamdocs.fnal.gov/DocDB/0018/001881/004/Corrector_specs_update%20after%20prototype%20060720.pdf
[6] Eric Prebys, "Modified three bump", Private Communication